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A MACHINABILITY EVALUATION OF CRYOGENICALLY TREATED BERYLLIUM COPPER IN A MAGNETIC FIELD ASSISTED BY ELECTRICAL DISCHARGE MACHINING

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ABSTRACT

Beryllium copper is known by its high fatigue strength, excellent wear and corrosion resistance and, non-magnetic material. And it finds application in electronic and electro-mechanical devices. But there are some problems in machining of beryllium copper by conventional machining processes. Thus, as a substitute for the conventional machining process die-sink, electrical discharge machining has gained importance for machining such materials. This study investigates the effects of work piece (Beryllium copper), tool electrical conductivity, magnetic strength, gap current and pulse time on the material removal rate, tool wear rate, white layer thickness and crack density. One-variable approach at-a-time was employed to find out the level of the process parameters. Response surface methodology has been used to develop the empirical models for response characteristics. Parametric analysis revealed that electrical conductivity, magnetic strength, gap current, and pulse-on-time affect the responses. Empirical model can predict material removal rate with R2 value of 97.69% and tool wear rate with R2 value of 93.75%. White layer thickness formed is less with a maximum value of 15 µm and negligible surface cracks were observed on the work piece using SEM images at 850X and 1000X.

KEYWORDS: Beryllium Copper, Response Surface Methodology, Material Removal Rate, Tool Wear Rate, White Layer Thickness & Crack Density

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Original Article

INTRODUCTION

Owing to the development in the material science and technology, advance material with striking material properties are produced in today's world. However, there are some problems in machining of such advanced materials, namely beryllium copper by the conventional machining processes. Its high strength creates a serious issue of surface integrity and tool wear. Thus, unconventional machining processes, namely electrical discharge machining process is the one which helps to overcome these problems. Pradhan et al. used AISI D2 tool steel as a work piece material. During pulse off & on time, the current were found significant parameters in their research. Shabgard et al. conducted experiments on FW4 welded tool steel. They used response surface methodology followed by the method of least squares to develop mathematical model. Kumar et al. used powder metallurgy electrode during electrical discharge machining of Hast alloy with a positive polarity. Results showed that, maximum material removal rate is obtained at an average value of the current, low value of voltage & current gives low TWR. Baraskar et al. in his study performed experiment on EN8 steel. They used response surface

methodology & regression analysis to generate an empirical model which predicts MRR, TWR & Surface roughness. Gill et al. studied the effect of copper, chromium and brass as tool electrode material during machining of EN-31 die steel by varying the pulse current at a positive polarity. Experiments showed that brass gives a better depth of cut and hardness. While the use of copper chromium gives better MRR & lower TWR. Uhlmann et al. optimized process parameters on dry sinking electric discharge machine. MAR-M247 is basically a Nickel based alloy used as work piece material. It is observed that gap current & pulse duration affects machining time. Surface roughness observed less than 6.3 μm. Zhao et al. conducted experiment on electrical discharge machine to improve the performance measures during machining of single crystal silicon carbide work material using copper foil by employing deionized water as dielectric media. For the study, they used different thickness of copper foil and tensioned foil to check its effect on EDM characteristics. They found that MRR increased & TWR decreased using foil electrode for cutting single crystal silicon carbide. Khan et al. experimented on stainless steel by applying external magnetic field. He applied N45 grade magnetic field. They obtained surface roughness (SR) value up to 2.4 micrometers obtained at alow current. Surface roughness increased for duty factor more than 50%. Makenzi et al. Checked the influence of magnetic field using Nd magnets. It is observed that high peak current increases the surface roughness & debris removal become easy due to magnetic fields. Teimouri et al. In his research used rotary tool accompanied with magnetic field. They considered different levels of energy. Continuous ACO algorithm applied to optimize electrical process parameters to increase MRR & reduce SR. Shivnandan and Singh used cryogenically treated AISI D2 to conduct experiment on electrical discharge machining. They found that the material removal rate increased by 10% by applying cryogenic treatment to work piece. Singh et al. conducted experiments on Cryogenic treated HCHC, EN8, EN 31 die steels. They found high values of MRR, less values of TWR & good surface finish in comparison with untreated workpiece. Mathai et al. performed experiment on stainless steel SS 304 as work piece material. They observed that TWR increases for electrolytic copper electrode with increasing gap current. MRR also increased with an increase in current. This study focuses on experimental investigation on the influence of gap current, magnetic field and cryogenic treatment of workpiece-tool on the electric discharge machine productivity aspects (MRR and TWR) and surface integrity (white layer thickness and surface crack).

MATERIAL AND METHOD

In this study experimentations were carried on Electronica Machine Tools of C400x250 model of die sink type electrical discharge machine. In this study negative polarity tool electrode with NC control in Z-axis is used for experimentation. Experiments were conducted by using the dielectric medium as commercial grade of EDM Oil. Throughout the experiments a side wise flushing pressure of 0.5 kg/cm2 is used. In this study beryllium copper alloy was employed as a work piece material. The material was purchased as a raw stock in the dimensions of 150 x 100 x 100 mm from the local market, and then cut into rectangular blocks of dimensions of 30 x 20 x 20 mm for the experimentation, high thermal conductivity copper is used in the study as a tool electrode material. The size of the tool is of ϕ6 mm x 90 mm length. It is machined to a square shape of 3 x 25 mm length using the indexing mechanism and a milling machine. Before conducting experiments work piece and tool electrodes were cryogenic treated from Kryospace, Pune, India. Electrical resistivity/ conductivity test was performed to determine the effect of cryogenic treatment of subjects, materials from NPK Labs, Pune, India. To apply external magnetic field neodymium magnet is used around the machining zone while performing the experiments. A digital weighing balance of least count 0.001 gm is used to measure the weight of work pieces and tool electrodes before machining and after machining. Square holes up to a depth of 5 mm from the surface

were produced on the untreated and cryo-treated BeCu work part using electrolytic copper tool electrode. Figure 1 shows the experimental setup which consists of BeCu workpiece, copper tool electrode and magnets utilized for experimentation. To measure the thickness of the white layer formed on the surface of the work piece, the each specimen is cut cross-section wise and were grounded with emery papers and then polished on cloth with 0.3 µm Al_2O_3 powder. White layer thickness of each specimen is then seen at magnification of 850× under scanning electron microscopy. Each specimen is observed under SEM and each micrograph is captured as an image file. Then an average white layer thickness is obtained for each sample. Then the machined surfaces were zoomed to 1000X magnification to measure the surface cracks in the wall and bottom surface of the hole. To study the effect of the process parameters namely gap current, magnetic strength and pulse on time, on the performance characteristics material removal rate, tool wear rate, white layer thickness and crack length. Constant parameters include gap voltage 55V, pulse of time 7 µs, commercial grade EDM oil was used as dielectric fluid, 0.5 Kg/cm^2 flushing pressure was used with W. P (-ve); T. E (+ve) polarity.

Figure 1: Experimental Setup

RESULTS AND DISCUSSIONS

Based on the pilot experimental results and literature review magnetic field, gap current and pulse on time levels were selected for conducting the main experimentations. In the present work, the machining variables considered for conducting experiments are magnetic field (T), gap current (I) and pulse on time (Ton). And to understand the effect of these input variables on the performance measures, namely material removal rate and tool wear rate. Three levels are selected for each of the variable which is shown in the Table 1. Table 2 shows the fifteen sets of trail conditions as per the Box-Behnken design. This design consists of full factorial design for three input variables, each of three levels. Analysis of variance (ANOVA) was carried out to identify the most significant parameter that affects the material removal rate and tool wear rate. ANOVA test was carried out at 95% confidence level, i. e. α = 0.05 level of significance. The multiple regression method is used to fit a linear function among the input and output variable by employing Minitab 16 statistical software.

Table 1: Input Variables with their Levels

Factor	Parameter	Levels		
		-1	0	+1
A	Magnetic field	0	0.248	0.496
B	Gap current	8	12	16
C	Pulse on time	13	26	38

Table 2: Design Layout with Observed Values

Exp. No.	Magnetic Field (T)	Gap Current (A)	Pulse on Time (µs)	MRR (mm^3/min)	TWR (mm^3/min)
1	0	8	26	2.32	0.071
2	0.496	8	26	2.221	0.080
3	0	16	26	6.002	0.332
4	0.496	16	26	6.547	0.315
5	0	12	13	1.936	0.158
6	0.496	12	13	2.042	0.160
7	0	12	38	4.662	0.149
8	0.496	12	38	5.003	0.166
9	0.248	8	13	0.966	0.068
10	0.248	16	13	1.882	0.195
11	0.248	8	38	2.897	0.044
12	0.248	16	38	7.400	0.215
13	0.248	12	26	4.862	0.164
14	0.248	12	26	4.643	0.201
15	0.248	12	26	4.789	0.206

From the table 3 it can be inferred that the gap current, pulse on time followed by square terms of pulse of time and interaction between gap current and pulse on time are the most significant variables that influences the material removal rate. Residual plots are used to understand the problems like non normality, non random variation, non constant variance, higher-order relationships and outliers. In the present study it can be seen that R2 value obtains is 97.69%, which means that the model can predict material removal rate with an error less than 10 %. And the adjusted R2 values obtained is 93.53%, which means that the data are well fitted. The multiple regression model formulated for predicting the material removal rate is given by equation 1.

$$MRR = 4.765 + 1.678*I + 1.642*Ton - 1.17048*Ton*Ton + 0.89700*I*To \quad (1)$$

From the table 4 it can be inferred that the magnetic strength, pulse on time followed by interaction between gap current and pulse on time are the most significant variables that influences the tool wear rate.

In the present study it can be seen that R2 value obtained is 93.75%, which means that the model can predict tool wear rate with an error less than 20%. And the Adjusted R2 values obtain is 82.5%, which means that the data are well fitted. The multiple regression model formulated for predicting the tool wear rate is given by equation 2.

$$TWR = 0.190847 + 0.099336*I + 0.001214*T - 0.000881*Ton + 0.003735*T*Ton \quad (2)$$

Table 3 ANOVA Table for MRR

Source	DOF	Seq. SS	Adj. MS	F	P
Regression	9	52.7937	5.8660	23.47	0.001
Linear	3	44.1997	14.7332	58.95	0.000
Magnetic Field	1	0.0990	0.0990	0.40	0.557
Gap Current	1	22.5289	22.5289	90.14	0.000
Pulse on time	1	21.5718	21.5718	86.32	0.000
Square	3	5.2574	1.7525	7.01	0.031
Magnetic Field*Magnetic Field	1	0.0227	0.1245	0.50	0.512
Gap Current*Gap Current	1	0.1761	0.3498	1.40	0.290
Pulse on time* Pulse on time	1	5.0586	5.0586	20.24	0.006
Interaction	3	3.3366	1.1122	4.45	0.071
Magnetic Field*Gap Current	1	0.1044	0.1044	0.42	0.546
Magnetic Field*Pulse on time	1	0.0137	0.0137	0.05	0.824

Table 3: Contd.,

Gap Current*Pulse on time	1	3.2184	3.2184	12.88	0.016
Residual Error	5	1.2496	0.2499	-	-
Lack-of-Fit	3	1.2246	0.4082	32.67	0.030
Pure Error	2	0.0250	0.0125	-	-
Total	14	54.0433	-	-	-

Table 4: ANOVA Table for TWR

Source	DOF	Seq. SS	Adj. MS	F	P
Regression	9	0.091106	0.091106	0.010123	8.33
Linear	3	0.078959	0.078959	0.026320	21.66
Magnetic Field	1	0.000012	0.000012	0.000012	0.01
Gap Current	1	0.078941	0.078941	0.078941	64.97
Pulse on time	1	0.000006	0.000006	0.000006	0.01
Square	3	0.011453	0.011453	0.003818	3.14
Magnetic Field*Magnetic Field	1	0.001927	0.001257	0.001257	1.03
Gap Current*Gap Current	1	0.000110	0.000321	0.000321	0.26
Pulse on time* Pulse on time	1	0.009416	0.009416	0.009416	7.75
Interaction	3	0.000694	0.000694	0.000231	0.19
Magnetic Field*Gap Current	1	0.000168	0.000168	0.000168	0.14
Magnetic Field*Pulse on time	1	0.000056	0.000056	0.000056	0.05
Gap Current*Pulse on time	1	0.000471	0.000471	0.000471	0.39
Residual Error	5	0.006075	0.006075	0.001215	-
Lack-of-Fit	3	0.005058	0.005058	0.001686	3.32
Pure Error	2	0.001017	0.001017	0.000508	-
Total	14	0.097181	-	-	-

It is a well known fact that electric discharge machining is a thermal erosive process. It is observed by many researchers that on the top surface of the work piece there are different layers deposited known as heat affect zone or white layer thickness. White layer consists of particles re-soildified on the work piece surface that is not flushed away. The unwanted material removed from the work piece gets deposited on the work surface which is not flushed away by the dielectric fluid. Based on the literature review it can be inferred that the white layer will have different layers and this number of layers vary from sample to sample. It is also observed that white layer is formed at all machining conditions whether it is machined using water or hydrocarbon oil as dielectric fluid. Average thickness of the white layer depends upon spark energy. For the present study it was observed that the formation of white layer is less than 20 µm which confirm that dielectric flushing is efficiently removing the molten metal from the work piece surface.

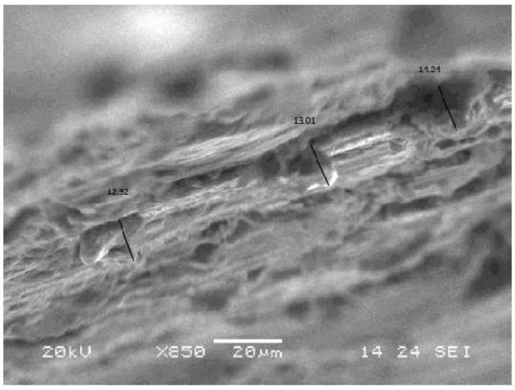

Figure 2: WLT at a Horizontal Cross Section of a Square Hole for High MRR

Electrical discharge machining is very complex and stochastic in nature, due to sudden localized heating and cooling process. The process consists of random strike of sparks of the work piece surface. During each sparking the temperature of the work piece goes beyond the boiling point of the materials. Because of this thermal feature of EDM process which involves heating, melting and vaporization followed by cooling, by dielectric flushing produces surface damage in the form of cracks. Thus, there is a growth of a high thermal stresses which exceeds beyond the fracture strength of the material. Theoretically cracks are developed due to thermal mismatch of molten metal that resolidifies at the work piece surface. They are formed on the machined surface and grow up to the recast layer. Usually white layer is composed of carbon atom that has a separate and distinct structure, which is distinguished from the parent material. Carbon atoms come from the hydrocarbon dielectric breaks down, which enter on the work piece surface. Thus the conditions become favorable for crack formation due to increased carbon content and alloying effects from the tool electrode, which in turn increases the brittleness of the white layer. Literature suggests that the length and density of cracks depend on the spark energy and thermal properties of the work piece material. The spark energy depends upon gap current, pulse on time and gap voltage. SEM images are taken for cut the section of the work piece. Images are taken at wall surface and bottom surface of the work piece. In general for low, medium and high material removal rate specimen has negligible surface crack due to the reason that work piece has good thermal properties and lesser white layer thickness formed on the work piece surface.

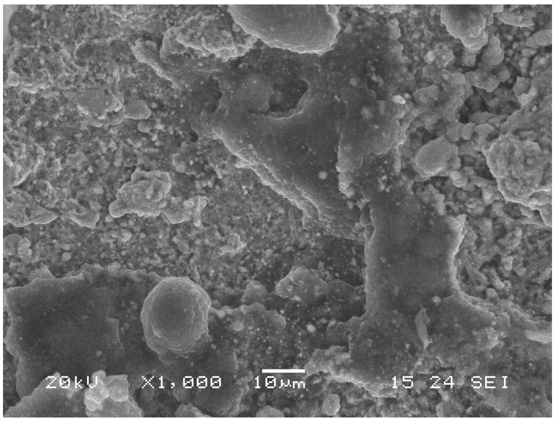

Figure 3: Cracks at Surface Bottom of the Square Hole for a High MRR

CONCLUSIONS

In this study square hole was cut on beryllium copper work piece using high thermal conductive copper tool electrode. This study includes work piece-tool electrical conductivity, magnetic strength, gap current and pulse on time as input variables and material removal rate and tool wear rate as output variables. Exploratory experiments were carried out to study and normalize the EDM machine settings and process responses. Experiments based on the box -behnken design were conducted to develop mathematical models to predict output variables. The EDM performance measures were modeled in terms of input variables using a design of experiments coupled with multiple regression method. Based on box behnken design it was found that gap current followed by pulse on time, square term of pulse on time and interaction of gap current & pulse on time are the most significant parameters which influence MRR. The multiple regression mathematical model developed has a R^2 value of 97.69%. The average percentage error based on the analysis shows about 10 %. Based on box behnken design it was found that magnetic strength, followed by pulse on time, gap current and interaction of magnetic strength & pulse on time are the most significant parameters which influence TWR. The multiple regression mathematical model developed has a R^2 value of 93.75 %. The average percentage error based on the analysis shows about 19 %. White layer thickness formed is less with a maximum value of 15 µm and negligible surface cracks were observed on the work piece using SEM images at 850X and 1000X.

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